SOIL FACTORS RELATED TO THE LOCAL DETERMINATION OF FOREST SITE QUALITY

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A Review of Literature

by

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TABLE OF CONTENTS

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INTRODUCTION

The science of forest soils, though relatively young, is represented by a large and ever-increasing volume of literature, including recently published textbooks by Lutz and Chandler (27)[2/] and Wilde (46a). The former appears to be more thorough and comprehensive. As is often the case with a new science, the literature in general is based on observation and limited experimentation. Much of it is basic or descriptive rather than being adapted to application on problems of forest management. At the same time, the practicing forester has started asking what he should know about soils in order to grow his trees more efficiently.

The study of field-crops and pasture soils has some application in forests, but there are many important differences (27). Forests require less nutrients than most other crops. Nutrients are returned to the soil through leaf fall, and harvest of the wood crop takes very little mineral content from the soil. Forests are the longest lived of all crops, and they have a profound influence on soil properties and some effect on climate. Particles larger than 2 mm. in diameter are ordinarily not considered in agricultural soils, but they may be quite important in forest soils. In general, physical properties are relatively more important and chemical properties relatively less important in forest soils than in agricultural soils.

When it comes to the practical use of soils knowledge in America, it is rather well agreed that an important starting point is in evaluating forest sites (3, 14, 29, 34). Coile (10) quotes both American and foreign sources to substantiate this idea. Wilde (46a) cites a European example where soil characteristics have a prominent place in the direct evaluation of site.

1/ A report prepared as partial requirement for a course of study undertaken at the State College of Washington during the Summer Session 1949.

2/ Figures in parentheses refer to the list of references cited at the end of this paper.

Other practical questions raised by foresters (34) include: (a) The relation of soils to various forest management problems, including establishment of natural regeneration, artificial seeding and planting, slash disposal methods, effect of wildfire, use of controlled fire, and logging; (b) effects of forests on soils; and (c) relation of the soil to wood quality. The element of site evaluation is present in many of these. This paper is largely limited to consideration of forest soils in their relation to the evaluation of the quality of the forest site.

THE FORESTRY PROBLEM OF SITE EVALUATION

Foresters (38) define site as "the combination of biotic, climatic, and soil conditions of an area." Site quality (38, 43) refers to the productive capacity of an area of forest land (a site), usually for a specific species or combination of species. Several methods have been proposed for evaluating site quality, the most widely used being site index and plant indicators. Limitations of existing methods prompt the search for better ones.

Site Index and Its Limitations

In Forest Terminology (38), site index is defined as "an expression of forest site quality based on the height of the dominant stand at an arbitrarily chosen age." It is the most universally used of all site measurements, but it has definite limitations and is subject to considerable criticism. Some criticism is rather general (10, 13, 29), but many specific points have been noted.

Cases are noted where site index has little or no relation to the ease with which natural regeneration is established (27, 29, 63). Growth of trees in early years (up to 20 to 40 years of age) sometimes shows little or no relation to their later growth, thereby rendering valueless height-over-age curves necessary in determining site index in young stands (10, 13, 25, 54). Chapman (8) pointed out that the shapes of the height-over-age curves for longleaf pine in old-field stands apparently differ from those of stands on areas that have never been cultivated. That stand density affects height growth is fairly well accepted (13, 15, 27a, 45), as is the effect of fire on height growth (41). The writer has personally observed both of these effects.

The very definition of site index recognizes that different height growth may be expected from different species growing on the identical site, and this is amply substantiated in the literature (7, 10, 13, 16, 17, 25, 36, 41, 57). Trees of the same species, but from different seed sources often grow at different rates when planted side by side. The relative effect of stand density on site index also differs for different species. Obviously, site index alone is of little value in comparing site productivity for different species, and this is often important.

Stoeckeler (41) reports wide variation in volume yields of aspen of consistent site index, and found the yield variation could be explained by subsoil differences.

Coile (10) mentions several of the above criticisms of site index and also points out that site index cannot be used satisfactorily in uneven-aged stands, partially cut stands, cutover areas, abandoned fields, or cropland that is to be retired to forest use. Erdmann (13) mentions many of these criticisms and points out that all variable growth factors must be uninterruptedly at an optimum before site index can be used even in theory.

Site index still has a place in applied forestry, but its limitations and the need for supplementary, or perhaps entirely new, criteria for site evaluation must be recognized.

Plant Indicators of Site Quality

Cajander's system for evaluating sites on the basis of ground vegetation is widely used in his native Finland and in Norway, Sweden, and Russia (50, 52, 57). On the American continent, the use of plant indicators has shown promise in Quebec (64, 67), in Lake States aspen (41), the Douglas-fir region (39), Pennsylvania (51), and as guides to planting in the Ohio Valley (16). Pearson (33) suggests that plant indicators may have value in the Southwest. Thomas (72) thinks the system may have possibilities in tropical Africa. Some authors mention correlation between indicator plants and certain soil characteristics (50, 55, 57).

It will be noted that the most successful use of indicator plants has been in the northern regions. Lutz and Chandler (27) point this out, and Arnborg (50) and Brantseg (52) state that plant indicators appear to be less reliable in Norway and Sweden than in Finland and have only very limited use in Germany. Erdmann (13) and Coile (9) go further and question the use of indicators at all. Coile bases his arguments on the supposition that roots of indicator plants do not occupy the soil body to the same extent that tree roots do, and that understory vegetation may be greatly influenced by variations in the forest it is supposed to evaluate. These arguments may be more valid in temperate than in northern zones.

There seems to be danger that men with ecological training may get overly enthusiastic about the possibilities of plant indicators. Spilsbury and Smith (39) review the general theory and present arguments for it, but fail to review limitations and arguments against it. The conclusion of Lutz and Chandler (27) is logical, that plant indicators should have some use in site classification, but that they also have definite limitations that must be recognized.

Environmental Factors as Measures of Site Quality

Since site is the combination of biotic, climatic, and soil conditions of an area, it would be theoretically possible to evaluate site completely and precisely in terms of the environmental factors that contribute to it, if these factors can be measured and integrated with sufficient precision.

We can scarcely hope to approach such an ideal in practice, for we cannot foresee the time when "natural" or "normal" variation can be eliminated. This need not discourage us from investigating environmental factors, for where there is sound theory, there is good chance of developing practical applications.

Environmental factors are commonly grouped into four categories (9, 27): climate, physiography (topography and basic geologic formations), soils, and living organisms. The interrelationships among these categories must, of course, be recognized, but each can be analyzed as a separate entity.

Climate, except in areas of extremely irregular topography, rarely varies greatly within small geographic areas. It is a primary factor in determining broad vegetative and edaphic regions, but climatic causes of local variations in site quality can ordinarily be explained or evaluated in terms of topography.

Physiography includes two distinct elements. The sub-category topography will have application in local site evaluation, most particularly in rough mountainous areas. Several investigators (5, 24, 30, 44, 53) found that topographic position, slope, or aspect may be related to site quality in areas of only rolling topography. Coile (10) found that effects of topography in the lower Piedmont of North Carolina could be entirely explained by more highly correlated effects of soils, but he also (9, 34) recommends that topography be included in any system for evaluating sites. Tarrant (42) and Lutz and Chandler (27) support this view. Moessner (31) reports that topographic features are of considerable use in preparing site maps from aerial photographs.

The physiographic (geologic) substrata are likely to be of more importance in forest soils than in strictly agricultural soils (27). Two reasons are advanced: 1. Forest soils are often relatively immature and, therefore, reflect the effect of their parent material in upper layers to a greater extent than do mature soils. 2. Tree roots may often penetrate into the substrata itself. The depth of the soil mantle affects the relative importance of underlying substrata to the site (9). On some sites, interlying features such as hardpan or water table relatively close to the surface will obviously limit the possible direct effects of parent materials. However, Lutz and Chandler (27) point out that in small regions of uniform climate, parent material is probably the most important

single factor in determining the character and productivity of soils, and that in some localities, ecological types are rather closely correlated with surface geology. They suggest further that in cases where parent material appears to have a direct influence on site, the conception of soil should be broadened to include the parent material. Tamm and Wadman (71) suggest that, in areas of roughly equal water supply, forest conditions can be correlated with type of bedrock (Sweden).

Soil as a primary factor in site quality has an ardent champion in Coile, who says (34): "In regions of uniform climate and gentle relief, the soil alone contributes most to site quality. However, in mountainous country other site variables include exposure, slope, and altitude. In generally flat land such as is found in lower coastal plain regions, the relative topographic position of any given area of land, may be a very significant factor in determining site quality." It is the writer's observation that, in the lower coastal plain of Alabama and northwest Florida, "relative topographic position" is often, but not always, reflected in the soil itself. Coile goes on to say, "Site quality of land for forest trees is determined primarily by the quality and quantity of growing space for tree roots," pointing out that this is expressed in soil factors. Lutz and Chandler (27), on the other hand, caution against a too complete reliance on soil factors and point out that climatic, physiographic, and biotic factors should always be considered. They also point out, as do Coile (9, 34), and Erdmann (13), that classification on a single soil factor should ordinarily not be attempted, and that the standard soil survey system for agricultural soils is often inadequate for evaluating forest sites. Lunt and Swanson (26) emphasize this latter point but go ahead and map forest soils under the standard system, at the same time deploring use of factors or relationships that are not already standard in soil mapping. To the writer, this position is untenable. If any situation can be improved by modification, it should by all means be modified.

Living organisms, the biotic category of environmental factors affecting site characteristics, are highly complex and not as well understood as are the other, more physical, categories. Coile (9) maintains that, though important, they can in large part be related to the soil itself. Lutz and Chandler (27) prefer the view that biotic factors may contribute directly to site and should be recognized as so doing. Special mention should be made of the biotic factors as they may actually change site quality, either by degradation or improvement (1, 2, 13, 18, 27, 54, 62, 65). Biotic factors are closely enough related to soil factors to justify discussion in a later part of this paper.

INORGANIC FEATURES OF THE FOREST SOIL

Parent Material

The general importance of parent material as it pertains to the influence of geologic substrata on site has already been discussed. The following cases are noted where a specific correlation between parent material and site quality was established.

Hill et al (19) found it necessary to include parent material as a soil factor in some cases to get good correlation between site index and soil factors in the Douglas-fir region. Colman (34) observed correlation between parent material and grade of timber stands in Montana. Gibbs and Ligon (16) report that planted red pine failed on soils with calcareous glacial till layers near the surface, but that black locust was universally successful on such soils and often failed on others. Stoeckeler (41) found significantly better volume growth of Lake States aspen (especially in the better sites) where the parent material was calcareous rather than acid, but where site index and other soil features were very similar.

In most of the literature in which parent material is mentioned, either no correlation was observed between site quality and parent material, or the correlation was better expressed in other soil factors. It may be concluded that, although parent material is significant in only limited circumstances, it should not be overlooked in developing a system for site evaluation.

Physical Soil Characteristics

Coile (9, 10, 34) places great emphasis on the importance of physical soil properties in determining site quality, almost to the exclusion of all other factors. In one review of literature (10), including several articles mentioned in this report, he goes to considerable length to point out that non-physical factors shown as significant by the original author might reasonably be closely related to unconsidered physical properties, usually those affecting the water and air regimen of the soil. He even suggests that site degradation and improvement can usually be evaluated in terms of physical changes of the soil. His general conclusion is that the most important factors are those which affect growing space for roots, aeration, and water availability, recognizing that the three may be interrelated.

Locke (24) and Tarrant (42) do not make such a strong case for physical factors, but follow Coile's lead by placing major emphasis on physical factors in the soil-based site-quality classifications suggested for middlewestern oak (Locke) and Douglas-fir (Tarrant). Plice (35) tends to substantiate one of Coile's arguments by suggesting that the generally believed superiority of mull over mor may be reflected in purely physical soil characteristics.

Pearson (33) suggests the importance of physical soil factors in southwestern (U. S.) forests, and De Rosayro (66) in Ceylon, but neither makes exclusive claims for these factors.

Lutz and Chandler (27) deplore the concept of physical soil factors being all-important, though they recognize the relatively high importance of them and the fact that many other properties are strongly influenced by them. This appears to be the safer view; Coile's theory may be entirely correct for some forest types or even regions, but it would appear unwise to apply it to all forests.

A single physical characteristic of the soil seldom determines site quality, but the general relationship of some individual characteristics may be discussed.

Soil texture as such seldom determines site quality, according to Lutz and Chandler (27), although a few investigators have apparently found that it does. Holtby (20) reports that the percent of silt plus clay, six inches below the surface, is a fairly reliable indicator of site index for Ponderosa pine on Underwood soils near Glenwood, Washington. Stoeckeler (41) found that average silt plus clay content of the A plus B horizons is a good indicator of site index for Lake States aspen; 50 percent was about optimum, with heavier and lighter soils both poorer. Repeated fires also influenced site index, as did height of water table on light sandy soils. Many other investigators considered soil texture as a very important factor, but with more supplementary or correlative factors than Stoeckeler uses.

Lutz and Chandler (27) present the following generalities concerning the relation of texture to site quality:

1. Loam soils are generally more favorable than coarse sands or heavy clays.

2. Deep coarse sands usually support poor forest stands.

3. Site quality usually increases with proportion of material under 0.2 mm.

4. Layers of fine-textured material in lower horizons may compensate for coarse-textured surface layers.

5. Very heavy clay soils may inhibit regeneration and subsequent growth.

6. Rocks or stones in heavy soils may be a decided advantage by causing increased temperatures and penetration of water and air. Quantities of rock up to about 20 percent of the soil volume may be desirable.

Soil structure, being a changeable factor, has not been related quantitatively to site quality, although many authors recognize its importance (2, 27, 42, 54). Lutz and Chandler (27), in discussing structure, point out that it strongly influences moisture relations and aeration as well as other physical relations such as pore space, air capacity, temperature, volume weight, and permeability. Many of these factors influence root penetration and other biotic activity. Lutz and Chandler also point out that, generally, a favorable soil structure is maintained by healthy forest stands of species adapted to the environment. From this it may be concluded that degredation or improvement of site quality may often be related to unfavorable or favorable changes in structure. Daubenmire (12) points out that rapid penetration of seedling roots into loose soils results in increased drouth resistance, and that light or loose soils "warm up" earlier in the spring, permitting earlier growth, due to faster equilibrium between air and soil temperatures, freer gas exchange, and modified moisture relations.

Pore volume, according to Lutz and Chandler (27) is important in determining air and moisture relations of the soil. High pore volume is usually associated with good site, low with poor. The most favorable condition may be where the high pore volume is about equally divided between capillary and non-capillary pore space.

The importance of air capacity and aeration has already been mentioned and is developed by several authors (10, 12, 27, 42). Lutz and Chandler (27) say that aeration is generally a function of air capacity, but poor drainage may result in poor aeration in a soil of high air capacity. They also point out that high air capacity may be associated with good site provided moisture relations are also favorable, and that a good, thrifty forest tends to maintain good air capacity in the soil. Daubenmire (12) mentions that masses of poorly aerated clay in the subsoil are often associated with unhealthy plant conditions. It may be concluded that, since air capacity and aeration are difficult to measure except in rather general terms, measurement of closely related factors will be more practicable in field evaluation of site quality.

Soil temperature is of greatest importance during germination and early life of the tree (27). Extremes in either direction are undesirable, if not actually dangerous. Temperature is also important in its indirect effects on water relations and biotic factors. It should also be noted that the forest itself has great influence on soil temperatures.

Soil moisture is considered by many investigators to be the most important single factor in determining forest growth (7, 14, 22, 27, 30, 33, 34, 71). Others who do not stress moisture to this degree have developed criteria of site evaluation based on soil factors that reflect moisture conditions more than anything else (4, 5, 24, 41, 59, 60, 73). Coile (10, 34) recognizes the importance of the

moisture regimen, but at the same time includes growing space for roots and aeration as quite important criteria. Lutz and Chandler (27) abandon much of their customary qualifying caution in discussing moisture relations. They say that soil moisture is a major controlling factor in forest growth and that occurrence of forest types is largely controlled by water supply. Site quality usually increases with water supply, but the trend is reversed if water exceeds a desirable maximum. Soil layers at lower depths must be considered, as fine-textured layers several feet below the surface may be highly important in moisture relations. Depth to water table is important; tables as deep as 16 feet may influence growth, and high tables may be either good or bad depending on species and other local conditions. Root competition for moisture is very important, and abundant moisture tends to offset lack of mineral fertility.

Drainage as a factor in moisture relations is stressed by several investigators (4, 5, 7, 22, 36, 73). Excessive drainage reduces site quality through creating temporary drouth conditions, whereas poor drainage is also undesirable. Pruitt (36) reports better height growth of planted loblolly and slash pines after the water table of North Carolina "pocosins" was lowered by ditching. The two species showed different responses to the improved drainage, loblolly benefiting best from the most complete drainage and slash pine from only partial drainage. Daubenmire (12) explains the detrimental effect of a high water table in terms of restricted root space, resulting in a dwarfed root system and small shoot. This may be due to poor aeration near the water table, with resulting lower temperature, reduced insolation, and increased fungal parasitism. On the other hand, the benefits of a "relatively high" water table (perhaps over 2 feet deep) are mentioned by several writers (27, 41, 59, 60, 61). Stoeckeler (41) found that, in light sandy soils of the Lake States, a water table 3 feet to 7 feet deep added as much as 15 feet to the site index of aspen, when compared with tables over 10 feet deep.

Soil depth, as measured either for the entire body or for specific horizons, is found or believed to be closely related to site quality by many (4, 5, 7, 10, 14, 17, 19, 22, 27, 33, 34, 37, 42, 44, 53, 73). In most cases, other soil factors were also used in evaluating site, but a few investigators found that soil depth alone accounted for site differences.

Roberts (37) demonstrated a direct curvilinear relationship between depth of surface soil and the height of 5-year-old planted black locust in Mississippi, but he recognized that other soil factors might have an influence on tree growth, especially as the trees grew older. Auten (5) reports that depth to tight subsoil is the most valuable measure for yellow poplar site in the Ohio Valley, with depth of A horizon a good supplement, but noted that topographic position must also be considered in rolling to steep lands. Site index was reduced as much as 30 feet by topography in

some cases. Day (53) showed a correlation between site index and depth of "free-rooting material" (to restricting rock or hardpan) in his study of larch, Sitka spruce, and Scots pine on Mynydd Ddu Forest, Wales, but also found elevation and slope to have significance in some areas. Most of the writers associate depth measurements largely with the soil moisture regimen, but others, notably Day (53) and Coile (10), also mention the element of root space.

Degree of erosion as a factor of site is mentioned by Gibbs and Ligon (16) in evaluating planting sites in the Ohio Valley, and by Kharitonovich (59) in the Russian Steppes. Cooper (11) found that South Carolina Piedmont site indexes were remarkably uniform (within 5 or 6 feet) on soils of the same series, type, and degree of erosion based on standard Soil Conservation Service erosion classes. A drop of 5 feet to 10 feet in site index was shown for each drop of one erosion class.

As was previously mentioned, most of the investigators who relate site quality to physical factors use several different criteria within the soil profile. Brief mention of the individual results follows: Harper (17) found that development of planted trees in central and western Oklahoma could be related to the percent of clay in the surface soil and in the subsoil and the depth of the surface soil. Hill et al (19), working with Douglas-fir, found good correlation between site index and Soil Conservation Service "soil profile units" (40), modified in a few cases by aspect and parent material. Locke (24) developed empirical yield tables for middlewestern oak in which he evaluated site in terms of aspect, depth to parent material, perviousness of B horizon, and texture of surface soil. Minckler (30) found that depth of A horizon and consistency of B horizon were of great value in evaluating planting sites in the Great Appalachian Valley. He added aspect and slope for certain species but noted that such topographic features were partially related to the soil factors used. Auten (4) found that site quality for planted black locust and black walnut in the Ohio Valley was closely correlated with thickness of A horizon and thickness and density of B horizon. Kuzniar (60) related site quality for pine, oak, and silver fir in Poland to depth of water table, accumulation of humus, proportion of particles smaller than 0.25 mm., and the variation of texture through the profile. Turner (44, 73) showed that site index for shortleaf and loblolly pines in Arkansas can be related to depths and textures of A and B horizons, considering also slope and exposure in the mountains. Chandler et al (7) report that their findings with loblolly and shortleaf pine in the Texas Coastal Plain agree very well with Turner's for the same soils in Arkansas, and that there is a close correlation between site index and soil series and type.

Special mention should be made of Coile's work (10) in correlating site index for pine with soil factors in the lower Piedmont of North Carolina. It is one of the most comprehensive investigations

of this nature ever undertaken. He found that factors contributing significantly to site index were: (a) Thickness of the A horizon; (b) ratio of silt plus clay to moisture equivalent of the B horizon; (c) the second power of the ratio; and (d) the imbibitional water value (difference between moisture equivalent and xylene equivalent) of the B horizon. He also found that the imbibitional water value was fairly consistent within recognized soil series and was more significant than the ratio of silt plus clay to moisture equivalent. He therefore concluded that site index could be estimated from the measured thickness of the A horizon and the standardized imbibitional water value (of B horizon) for the field-identified soil series. Factors measured, but not found to contribute significantly to site index, included total depth to C horizon and topographic position.

It is interesting to note that the three instances (7, 10, 11) where soil series and type proved useful in site evaluation were all in the shortleaf-loblolly pine forest type of southeastern United States. This suggests that standard soil mapping may be of considerable value in site classification within that type region. If so, it will be a material aid to field mapping of forest sites. It does not seem likely that soil series and type will prove useful in many other type regions, but there remains a possibility, especially in the South.

Chemical Factors in the Soil

It is apparent from the preceding discussion that many investigators feel that physical soil properties are all-important in site evaluation and that chemical factors have no useful purpose. Lutz and Chandler (27) state that, while this is undoubtedly true in many instances, generalization is not valid. Casual consideration of chemical properties can be explained by the fact that trees are relatively low users of nutrients, that fertility is often well maintained by annual leaf fall, and that there are frequent cases of compensating or other limiting factors that offset nutrient deficiencies. Dr. L. C. Wheeting has suggested, in a discussion with the writer, that apparent low nutrient requirements of forests may be due in part to the fact that trees absorb nutrient elements slowly over an entire growing season, whereas many other crops complete growth and maturity within a few weeks. In many agricultural crops, emphasis is on fruit or foliage yield, both of which require relatively greater nutrient supplies than does the wood crop of a forest. Thus forests may get sufficient nutrients from supplies too slowly available to be adequate for other crops.

Lutz and Chandler (27) point out that fertility can be well maintained by development of healthy, full stands of species adapted to the site. Such stands usually allow maximum development of the nutrient cycle. They suggest that chemical properties are more important at the northern thermal limit of a species range than at the southern. Hardwoods generally require more nutrients than conifers, and pines generally are the least exacting species. These relationships also vary with age of the tree.

Mineralogical composition of the soil, according to Lutz and Chandler (27), has considerable ecological significance. Soils with a wide variety of minerals are usually more productive than those of less varied composition. Soils with low percentage of quartz or high percentage of heavy minerals (specific gravity greater than 2.680) are more productive than those with the proportions reversed. R. W. Harder has observed (see Plair, 34) that western white pine soils with high moisture holding capacity and high mica contents in the B horizon support the best stands. Wittich (74) shows that the forest productivity of north German sandy soils of the diluvial region is very largely determined by the silicate content of the basic material, and that soils with a high content of silicates are capable of bearing fine stands of hardwoods.

Nitrogen requirements of trees vary widely with species, according to Lutz and Chandler (27). Hardwoods are most exacting and pines least. Significant growth increase has resulted from nitrogen fertilization of northern hardwood species, but other fertilizing experiments failed to show results. Nitrogen may be deficient in some forest soils. Lunt (61) found a slight correlation between total soil nitrogen and site index of second-growth oak in Connecticut, but placed more importance on water table and humus type. Holmgren (56) found a direct correlation between the nitrate nitrogen in the soil and the yield of Lombardy poplar in Chile (?), but no correlation with depth of soil or amount of soluble phosphate, potash, or lime. Harper (17) mentions that nitrogen may sometimes be a limiting factor in tree planting in central and western Oklahoma. Coile (10), in commenting on literature, suggests that when the nitrogen content of the A horizon shows a high correlation with site index, it may usually be a reflection of improved moisture conditions for growth of vegetation and subsequent decay of organic matter. It is, of course, widely recognized that nitrogen content is often closely related to the quantity and conditions of decomposition of organic matter.

Phosphorus, according to Lutz and Chandler (27), is somewhat deficient in forest soils, but the problem of requirements is very complicated. Again, hardwoods are apparently more exacting than conifers. Kessel (58) reports, however, that certain Eucalyptus species will grow 250 feet tall on Australian soils too poor to support Monterey pine. He goes on to say that total P_2O_5 content of the soil has proven a useful indicator of site quality for pine species, and suggests that available P_2O_5 might be even more reliable. Phosphate availability is related to acidity. McComb and Kapel (28) report that black locust and green ash seedlings planted in southern Iowa on an acid, glacial, clay subsoil exposed by erosion showed tremendous response to addition of $Ca(H_2PO_4)_2$, but very little to addition of NH_4NO_3 or $CaCO_3$. Neilson-Jones (32) reported that growth of planted pine in Dorset, England, was considerably improved by application of bone meal or basic slag, but attributes it to improved biotic conditions, as similar results were obtained from other non-phosphate treatments.

Calcium relations in forest soils, as reported by Lutz and Chandler (27), are rather complex. They point out that soils with relatively high ability to supply lime are commonly better sites than those with a low ability, but a high calcium concentration may be unfavorable for some species. Instances where calcareous substrata apparently influenced site (16, 41) have been noted already, but several investigators found no relationship. Lime is usually associated with non-acidic soils, but Lutz and Chandler (27) point out that acid organic soils usually supply adequate calcium, and that lime deficiency is more likely to be associated with highly acid mineral soils. Suchting (69, 70) reports improved growth following liming of certain German forests, but attributes the effect largely to reduced acidity or counteraction of site degradation. He also says that acidity-nutrient interrelationships are highly complex.

Even less is known about the relations of other nutrient elements in the soil. Lutz and Chandler (27) suggest that very sandy soils may occasionally be potash-deficient and that magnesium and iron may occasionally be deficient, particularly in surface layers. Magnesium, aluminum (soluble), nickel, cobalt, and chromium may sometimes be present in toxic quantities, but the interrelationships of toxicity, deficiency (of other elements) and acidity are highly complex. Leyton (23) points out that the toxicity-deficiency-acidity relationships are sometimes quite different for different species. He also quotes H. L. Mitchell's four degrees of nutrient status:

1. Minimum region where a particular element is limiting.

2. Working region equivalent to that commonly found under natural conditions.

3. Tension region where increase (or decrease?) in a particular element has no effect on growth.

4. Toxic region for a particular element.

This classification appears to have merit in the rationalization of nutrient problems, and it also suggests that problems of deficiency and toxicity are likely to be exceptional rather than common.

Analysis of nutrient situations is a complex problem. Soil analysis often fails to develop fundamental soil-plant interactions, and for this reason Leyton (23) and Lutz and Chandler (27) favor foliage analysis or plant-growth measurement for nutrient conditions. Kessell (58), on the other hand, thinks that plant tissue analysis has little practical value. Certainly the difficulties of adequate nutritional analysis curtail its practicable use in site evaluation.

Soil acidity was mentioned briefly in the discussion of calcium. Daubenmire (12) and Lutz and Chandler (27) agree that pH probably has little direct effect on tree growth and that most trees have a wide pH tolerance. Seedlings are more sensitive than older trees and generally develop best in pH range 4.5 to 6.0. Acidity is important in its interaction with other factors. Often it is associated with limitation of available nutrients or with toxic effects of mineral elements. High acidity tends to inhibit growth of bacteria and earthworms and interferes with nitrification and function of some decay organisms, thus allowing accumulation of organic residues. Alkalinity may favor damping-off fungi, eelworms, and other undesirable organisms. Suchting (68, 69) places more emphasis on acidity but recognizes the complexity of its relationships. He concludes (68) that conditions for good growth of forest trees include: no exchangeable acidity, pH higher than 4.5, at least one unit difference between pH in water and in KCl solution, low soluble aluminum, good nutritional status, and little or no humus in the A_0 horizon. Lang (21) reports that European larch grown south of its optimum range develops adequately only on soils poor in lime and hence acidic. It is not selective as to soil in its optimum range. Wheeting (46) suggests that relative acidities, or changes in acidity, may play an important part in forest site degradation.

Lutz and Chandler (27) suggest that buffer action may have some importance. A high buffer capacity is usually considered desirable; siliceous sands and the A_2 horizon of podzols are poorly buffered.

ORGANIC FEATURES OF THE FOREST SOIL

Since very close relationships exist between the dead organic matter in the soil and the living organisms in it, it seems logical to consider them more or less together. Lutz and Chandler (27) point out that in relating soils to silviculture the upper layers, particularly organic layers, merit special attention. Most feeding roots of trees are located in these layers, and the upper horizons are those most easily modified by silvicultural operations. It should also be pointed out that organic-biotic relationships in soils vary widely between climatic zones, since temperatures and moisture relations are closely related to biotic activity. This broad subject is only developed casually in this paper.

Litter and Humus

The following general discussion of litter and humus is developed from Lutz and Chandler (27). They point out that humus may serve either a positive or a negative purpose in forest production, and that it functions in the physical, chemical, and biological properties of the soil. A theoretical "highest soil fertility" from a "most desirable" humus condition is not always practical or even logical in forest management. The broader aspects

of silviculture should govern, with soil organic matter a secondary result rather than a primary objective. Generally speaking, rapid decomposition of litter is desirable to allow rapid mineral nutrient turnover, to avoid excess acidity with attendant ills, and to provide better moisture conditions. Thus a mull-type litter is generally considered better than mor, especially for hardwoods; but production is sometimes higher on mor soils than mull because of other factors influencing site quality. Mull may sometimes actually be "too rich" for some coniferous species.

Pearson (33) considers soil organic matter especially important in the Southwest, largely because of its importance in moisture relations. Wheeting (46) holds that "the humus layer of the forest is the keystone of successful forest management," and that maintenance of desirable humus conditions is to the forester what crop rotations and fertilizers are to the agriculturist.

Several authors (18, 32, 62, 65) report greatly improved growth from application of litter or compost to young plantations, or natural regeneration on soils initially poor. Gibbs and Ligon (16), on the other hand, derived only slight temporary benefits from mulching plantations on eroded lands in the Ohio Valley and concluded that the treatment had little or no value. British authors (32, 62, 65) attribute the improved growth on poor health soils in Dorset to improved biological activity following mulching.

Lunt (61), in his study of second-growth oak sites in Connecticut, found that mull soils had the highest site index and fibrous-mor-over-podzol the lowest. Arend (1) mentions organic matter relationships as contributing to hardpan formation and subsequent site degradation in the Landes Region of France. Heiberg (18) reports better height growth of plantations on mull soils than of those on mor soils, but does not develop an explanation. Daubenmire (12) points out that high-cellulose plant residue, such as occurs in forests with heavy litter and duff accumulation, lowers the available nitrogen because nitrogen is used by cellulose-decomposing bacteria. Wheeting (46) stresses the differences between species in the decomposition of leaves. Initial decomposition products are slightly to strongly acid; later products from some species are still slightly acid, but later products of many species are slightly alkaline. He considers these differences highly important in relation to soil nutrition, development, and degradation.

Soil Organisms

Soil organisms, in the broadest sense of the term, include everything from bacteria, algae, and protozoa to burrowing mammals and the trees themselves. They range from highly beneficial to definitely detrimental. Their interrelationships and relationships to other environmental factors are highly complex, and only a few can be mentioned in this report.

Lutz and Chandler (27) suggest that the silviculturist should consider the creation and maintenance of forest conditions favorable to an active soil fauna, to maintain site productivity. As usual, they stress the importance of "developing full stands of healthy trees adapted to the site." Earthworms and millipedes are associated with prompt disintegration of temperate-zone forest litter and the formation of coarse mull (both desirable site conditions), but earthworms are reduced in number by high acidity, coarse soil texture, excessive dryness, and mor-type humus layer.

The importance of mycorrhizal roots as aids to tree growth, especially on poor soils, is also stressed by Lutz and Chandler (27). Mycorrhiza apparently function as additional roots and increase the absorbing surface of the plant; they are especially important in the competition for available nitrogen. Rayner (65) attributes improved tree growth following composting of poor health soils in England to generally improved biological activity; Neilson-Jones (32, 62) goes further and attributes the improved growth to resumption of normal mycorrhizal development following compost-produced limitation of growth of toxin-producing organisms. Gale (54) observed an apparent increase in site index after trees were 20 to 25 years old (Isle of Man), which he attributed to a change from a "hard heathery moorland soil devoid of life" to an "open active soil containing a fair number of worms and fungal life with a sufficiency of humus."

Wheeting (46) stresses the importance of the forest itself on the actual development of the physical and chemical properties of the soil; the species present may determine the soil type. Cady (6) presents an actual case. On the same parent material (glacial till in the Adirondacks) with identical climate, radically different soils are found under different timber types. Under spruce-hardwood type with Viburnum-Oxalis ground cover, a podzol is found, with its characteristic low values for pH, lime, base saturation, and heavy mineral content in the A horizon and much higher values (each factor) in the C horizon. The soil under the northern hardwood forest (birch-beech-maple-basswood) with Arisaema ground cover is a brown podzolic soil with uniformly high values for pH, lime, base saturation, and heavy mineral content throughout the profile. Wheeting's (46) suggestion of differential leaching attributable to differential acidity of litter from different species could be used as an explanation.

CHANGES IN SITE QUALITY

Several references have already been made in this paper to degradation or improvement of site quality related to changes in the soil or soil conditions. A brief review and summary of these phenomena appears appropriate at this point.

Degradation of Site

The detrimental effect of fire on site is widely recognized; perhaps too widely, for there are recognized uses for fire as a silvicultural tool. Stoeckeler (41) found that repeated fire in Lake States aspen lowered site index by 6 to 25 feet, the greater reductions being on the lighter soils. Erosion is also widely recognized as detrimental to site. Removal of litter is a common degrading practice in some sections of Europe (12, 48). Daubenmire (12) attributes the degradation to physical, rather than to chemical, changes, but a German reference (48) suggests the opposite in the statement that growth on such areas may be improved through fertilization. Intense podzolization, resulting in development of a podzol soil, is the major soil phenomenon associated with degradation, but two references (47, 49) suggest that laterization may cause degradation of tropical rain-forest soils. In the development of a podzol, extreme leaching of the A horizon is followed by heavy accumulation of organic, iron, and aluminum colloids in the B horizon, often to the extent of hardpan formation. The effect on growth is twofold: nutrients are removed from the leached layer, and the hardpan restricts root development and water movement. Arend's (1) report of site degradation in the Landes region of France, following afforestation with pine, follows this pattern. Kittredge (20a) says that such degradation may be expected both in northern countries and in central countries where pure stands of spruce and pine have been planted outside of and below their natural range. Kittredge also says that examples of the latter are rare in the United States.

Daubenmire (12) and Lutz and Chandler (27) suggest that the accumulation of a heavy duff or litter layer may in itself be site degrading, probably through reduction in available nitrogen. Erdmann (13) places considerable emphasis on the susceptibility of a site to degradation as a factor to consider in evaluating the site.

Improvement or Rehabilitation of Site

Not all site degradation can be corrected; some may be wholly correctable, some only partly, and some not at all. Badly burned or badly eroded sites may require generations to regain even minimum productivity. Erdmann (13) would consider ease of rehabilitation as one factor in site evaluation.

Auten (2) points out that the productivity of eroded and other "misused" soils must be restored before the original climax forest can be grown. The rebuilding involves a change from xeric to mesic condition and can often be accomplished with a preliminary crop of pre-climax species. The degree to which the soil profile has been rebuilt can be judged by the amount of litter on the soil surface, the depth of organic matter incorporation in the A horizon, and the increase in the rate of water infiltration.

Daubenmire (12) and Lutz and Chandler (27) suggest that degradation due strictly to accumulation of excessive litter and duff can be relieved by thinning the stand (the heavier the better), other cutting and logging, or in some cases by burning.

Improvement of plantation sites through mulching with litter or compost has already been mentioned under the heading of "Organic features of forest soils" (18, 32, 62, 65). One German writer (48) reports that fertilizing may improve growth on areas disturbed through unsuitable choice of species, litter removal, and other human influences. Lime was the most successful amendment on actual trial. Suchting (70) found liming to be an effective means of counteracting degradation expressed in "leaching and related phenomena." Liming would therefore appear to be one means of counteracting podzolization, presumably resulting from "unsuitable choice of species." This would fit in well with Wheeting's (46) suggestion concerning podzolization, that it may result when a species producing acid-decomposing litter is planted on soil originally supporting a species producing neutral-decomposing litter. A return to a species better suited to the site (less acid litter) is an obvious alternative.

INTERRELATIONSHIPS AMONG SOIL FEATURES; SYSTEMS FOR CLASSIFYING SITES FROM SOIL FACTORS

The close relationships between specific soil factors has been mentioned at many points throughout this paper. The extent and complexity of these interrelationships cannot be emphasized too strongly. At the same time, the existence of interrelationships often makes it possible to use an easily measured factor for site evaluation, when some other difficultly measured factor is the real cause of differences in growth rates. This forms the basis for Coile's (9, 34) contention that within a zone of uniform climate, site can be measured in terms of topography and physical soil factors, both relatively easy to measure. At the same time, there is danger that such simplification may lead to error. Coile's theory may not hold in all, or even most, climatic zones.

Coile suggests (9) that a satisfactory system for evaluating site in terms of soil (within uniform climate) can ordinarily be developed using only the following factors:

1. Aspect.
2. Relative topographic position and slope.
3. Texture and thickness of A horizon.
4. Texture and thickness of B horizon.
5. Nature of substratum or parent material if relatively near the surface.

The first two factors (topographic features) he considers to be more important in northern latitudes than in southern. In later writings (34) he modifies the soil texture factors by suggesting that the nature of the clay fraction (amount and kind of colloidal clay) is also important.

Lutz and Chandler (27) are more conservative in their recommendation. They caution against trying to evaluate site in terms of a very few soil characteristics and point out that correlation between soil and site improves as the soil classification criteria are broadened to reflect as completely as possible the entire ecological complex. One can only apply such a theory in the light of the law of diminishing returns: when an added factor does not improve the estimate of site quality commensurate with the difficulty of measuring the factor, it should not be used. The soil characteristics that Lutz and Chandler believe to be most important from the standpoint of forest production, and by implication those that should be considered in working out site evaluation systems, are as follows:

1. Characters relatively permanent:
   - a. Thickness and texture of A horizon
   - b. Thickness and texture of B horizon
   - c. Texture and structure of C horizon
   - d. Nature of underlying strata with respect to permeability to water and roots
   - e. Nature of parent material with respect to calcium content
   - f. Position of water table
   - g. Content of rock in soil
   - h. Slope (degree and topographic position)
   - i. Aspect
2. Characters subject to appreciable change during relatively short periods of time:
   - a. Humus layer type
   - b. Nitrogen content of surface soil layers
   - c. Structure of surface soil layers

It will be noted that these characteristics include practically all that have been mentioned as significant in this paper, except ease of degradation and rehabilitation, and possibly some factors concerned primarily with planting or natural regeneration rather than with productive growth periods.

Erdmann (13) discusses soil-site classifications from a more philosophic point of view. His resulting suggestions for site evaluation are more in the nature of broad principles than specific factors, but are worthy of mention in that respect. He would consider the following:

1. Species for which evaluated.
2. Basic soil quality from permanent characteristics.
3. Susceptibility to degradation, permanent characteristic.
4. Current "health" of soil (actual degree of degradation), a temporary characteristic.
5. Ease of management, a relatively permanent characteristic, including ease of correcting poor "health," ease of controlling weed species, etc.

This general outline appears comprehensive enough to include all factors of soil that could influence site quality, and anyone attempting the problem will do well to consider it. Actually, according to the translator, Erdmann uses "soil" as practically synonymous with "site," so that he may intend that certain features of climate and topography be included.

SUMMARY AND CONCLUSIONS

It appears from this review of literature that soil factors may be of considerable value in evaluating forest site quality in many, if not all, forest regions and types. The exact factors to be used will undoubtedly vary widely from one region or type to another. In some regions the relative stability of soil factors, or the ease with which site may be degraded or rehabilitated, may be of considerable importance; in other regions it may be of little importance. The purpose of the evaluation must be considered, for different factors are more important in the regeneration and early growth of trees than in the later growth and development, and different species have different requirements throughout their life.

Easily measured factors are preferred to those less easily measured. Plant indicators may have value in indicating basic site conditions in some regions, but their relationships must be carefully and thoroughly established. Before any factor can be used in practical field classification of site, it must be related to an ultimate production criterion, preferably annual yield of merchantable (or potentially merchantable) wood volume. A review of general and specific soil factors most likely to be of value in site evaluation is presented in the section on <u>Interrelationships among soil features; systems for classifying sites from soil factors</u>. In many regions, physical soil factors, particularly those that relate to moisture conditions and root development, appear to be most important; but nutritional, organic matter, and biotic factors may also be important in some regions, or under special conditions in any region, and should not be overlooked.

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Author's Supplementary Note

This report was prepared within a limited time, and is not considered to be either complete or fully comprehensive. Several important references were omitted because of lack of time, and a more thorough search of literature would undoubtedly reveal a number of additional valuable references on limited parts of the field of forest soils.

Anyone making a comprehensive study of the subject of forest soils in their relation to site quality would do well to review the following references, in addition to those listed in the bibliography.

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